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SOVIET ELECTROINTEGRATORS AND THEIR POTENTIAL USES FOR DESIGN AND ENGINEERING CALCULATIONS

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The development of mechanization and automatization of production processes in machine building is connected with the execution of a large number of calculations. The calculations facilitate the finding of optimum designs for elements, units, and whole mechanisms, as well as the selection of the best operating conditions for mechanisms and machines.

In the Soviet Union there have been created new mathematical machines and electrical models which will allow mechanization of calculating and computing operations.

The rate of calculation is thereby so accelerated that designers, reseachers, and inventors are presented with completely new possibilities.

This report examines the various types of mathematical machines -- electrointegrators -- which are produced in the Soviet Union and, as examples, describes the method for solving some typical problems of interest to machine-building industry workers.

It is to be noted that the qualification of engineer is sufficient for persons solving problems with these devices. This is because the electrointegrators are universal physical models of those phenomena which have to be studied. Therefore, on the basis of the simplest analogies between the phenomena being studied and the phenomena in the model, any engineer can set up and solve concrete engineering problems without a great deal of knowledge in the field of computation technique.

When electrointegrators or electrical models are used, there is no numerical computation in the usual sense. The engineer who uses the electrointegrator is conducting experiments analogous with those which he would want to carry out on

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the mechanisms with which he is concerned. The practice of working with electrointegrators is analogous to the usual investigations in any given field of engineering, and may be accomplished in plant laboratories and design offices.

Characteristics of Electrointegrators

First of all, let us examine some of the general characteristics of electrointegrators. Figure 1 [appended] shows an over-all view of the type EI-12. The upper part of the vertical panel holds resistance boxes and the left part of the table holds condensers. Basically, therefore, the device consists of resistances and capacitances. The panel is a sort of "electrical drawing board" where, as on a real drawing board, any geometrical figure -- the profile of a design or section of a unit or part, for example -- can be set up. Beneath the vertical panel are the voltage and current dividers which permit the creation of various loads and external forces in testing the designs.

The measuring equipment is located at the center of the horizontal panel. With it, the voltage and currents at any point and in any element on the panel can be measured, and a study made of the phenomena taking place in the model.

The electrointegrator takes its power from a 220- or 110-volt, 50-cycle municipal line.

The type EI-12 electrointegrator is designed to solve many problems: (a) calculation of thermal areas in electric furnaces; (b) to determine stresses during distortion of shafts of complex section, etc.

The mathematical equations which can be solved on this type of electrointegrator have the form

$$\frac{\partial}{\partial x}\left[A_x(x,y)\,\frac{\partial u}{\partial x}\right] + \frac{\partial}{\partial y}\left[A_y(x,y)\,\frac{\partial u}{\partial y}\right] = F(x,y)$$

which represent partial differential equations of the elliptical type (Laplace, Poisson, vector potential equations, etc.).

The type EI-31 electrointegrator is distinguished from the EI-12 in that the EI-31 has capacitance boxes and also equipment for assigning voltages in the form of arbitrary functions of time. This integrator is used mainly to solve complex heat problems and problems in other fields, e.g., distribution of electrical and magnetic force lines in apparatus, hydraulics problems, and others.

The type ELI-14 vacuum-tube integrator of the Penza calculating-analytical machine plant can be used for the analysis of various physical phenomena in the most diverse fields, e.g., for investigating systems of automatic regulation and control.

This integrator permits solution of the most difficult problems arising during the designing or adjusting of automatic regulation systems, namely, the problem concerning the effect of the various parameters of the regulators and the regulated object on the speed and character of transient processes; the problem of the stability factor, the selection of optimum parameters, etc.

This integrator can be used to study the processes of regulation of temperature, voltage, speed of machines, and other quantities.

It can be used to investigate dynamic transient processes in mechanical setups, processes connected with the study of free and induced oscillations in complex electromechanical systems, and also follow-up systems.

The integrator is fed through rectifiers from the municipal ac line.

The larger type ELI-12 vacuum-tube integrator is used to solve a complex system of equations.

Vacuum-tube integrators serve for modeling and analysis of processes in technical equipment which (processes) are approximately described by a system of ordinary linear differential equations with constant coefficients, of the form:

$$\sum_{l=1}^{n} b_{kl} \frac{du_l}{dt} + \sum_{l=1}^{n} a_{kl} u_l = A_{k0}$$

where $k = 1, 2, 3 \ldots n$.

In the ELI-14, $n = 6$ and $b_{kl} = b_{lk}$, with arbitrary initial conditions. The coefficients of the equation may be set up from -100 to +100% at 1% intervals of the maximum value. Error in regulation of coefficients does not exceed 1% of their maximum value.

Heat Calculations on Electrointegrators

In the study of processes in forging and stamping production, in welding and in foundry practice, the study of heat processes occupies a prominent position. Electrointegrators can play an invaluable role in these cases.

Let us examine, for example, the possibilities which now exist for studying and calculating heat processes.

We shall take some part which has to be heated to a certain temperature. The form of this part can be arbitrary. It can be reproduced on the main panel of the electrointegrator exactly as on a drawing board. The geometrical scale is so chosen that the part to be studied will take up most of the panel.

The material in the part is characterized by certain physical constants for the heating processes: specific heat capacity and specific heat conductivity. On the basis of this data known from technical handbooks on the material, the constants of the electrical circuit can be determined. The formula for determining these values is extremely simple.

$$\frac{c_p \gamma l^2}{\lambda t} = \frac{R c n^2}{t_e}$$

where c_p is specific heat capacity, λ, specific heat conductivity; t, a unit of time equivalent to one second, R, resistance of the integrator element; c, capacitance of one integrator element; t_e, time in the electrointegrator corresponding to one second of the real process; l, unit of length, e.g., one cm; n, number of elements of the model per centimeter of the part, and γ, density.

Let the part be heated from any external heat source. During this process, the temperature of the heat source and the coefficient of heat transfer between the source and the material in the part are usually known. In the electrointegrator, the heat source is represented by the source of electric current. Between current source and model are conductances which reproduce the heat-transfer phenomenon of the medium between the heat source and the part.

With a voltage divider and resistance boxes, any coefficients of heat transfer can be established on the periphery of the part and the intensity of the heat sources can be varied. To convert assigned values for intensity of

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heat source and coefficient of heat transfer to corresponding voltage and conductivity values is an elementary operation using, for example, a formula

$$a = \frac{1}{R_0}; \; b = \frac{2}{n}; \; c = \frac{V_0}{R_0};$$

in the formula for boundary conditions

$$a\theta + b\frac{\partial\theta}{\partial n} = c$$

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Here, V_0 is voltage of current source, R_0 is resistance between current source and element of the model; θ is the temperature of the part; and a, b, and c are the assigned coefficients.

After the integrator has been turned on, voltages appear at all points of the model. The change of these voltages with time then corresponds to the temperature change during the heating of the part.

If it is required to determine the temperature inside a body of complex configuration, then the electrical model of the body is split up over a number of separate panels. It is then possible to feed current to each panel and to measure current or voltage at any point without disturbing the processes taking place in the model. In this manner, problems of temperature determination at any internal point of a complex body being subjected to heating are easily solved on the electrointegrator without thermocouples and under conditions where it would frequently be impossible to measure temperature.

The importance of temperature distribution in heated parts is a well-known fact. Large drops (gradients) in temperature cause internal mechanical stress in materials, occasion cracks and, under certain conditions, subsequent failure. The selection of heating conditions under which permissible gradients are obtained is of great interest to many industries.

It should also be noted that the induction and other methods of heating can be reproduced on the electrointegrator.

In foundry practice, there is much interest in the study of the temperature fields in metal during cooling in molds. This problem can be approximately solved on the type EI-31 electrointegrator.

For example, take the case of temperature distribution inside a cruciform profile which is heated to some maximum temperature and then cooled with the external medium at constant temperature.

In this case, all condensers of the electrical model receive determined charges and have the assigned voltage at the initial moment of the process. External points of the model are connected with the elements of the surrounding medium by resistances. Starting with this initial moment, the condensers of the model are discharged through the resistances, and the voltage distribution with time corresponds to the distribution of temperatures in various points of the body. The measurement of voltages (temperature) is conducted by a simple method at the model.

The solution of these problems is sufficiently accurate for practical purposes, constituting 2-5% of the maximum temperature.

It should be noted that electrointegrators are produced by industry as apparatus for solving a great number of typical problems. However, the practice of using electrical modeling in the conduct of engineering calculations has shown the expediency of creating working models of objects which are of constant interest in each given field of engineering, for example, models of massive concrete structures, bridges, dams, thermal processes in blast furnaces or open-hearth furnaces, petroleum deposits, etc.

The number of these models built for individual but extremely important problems is very large. For this reason, we consider it expedient to create for machine building also those special models which (in contrast to electrointegrators) are suited for particular problems, e.g., foundry practice, welding problems, and forging and stamping production.

In this case, the models can be prepared from less expensive elements and built in such a way that they can be used to obtain rapid answers to the problems of each given field. The graphic quality of the electrical model, from the geometrical standpoint, the extremely simple analogy between the constants of the model and the object being studied, and the simplicity of measurement methods recommend the electrical models for broad application.

It is to be noted that all parameters and quantities are established, on electrical models, with limited accuracy (of the order of 1% of maximum). Therefore, the accuracy of solutions to problems is also limited and depends on the character of the problem being solved. However, the limited accuracy of the electromodeling method appears to be no impediment in technical research, in the majority of cases. Generally, the physical constants, the dimensions of the field being studied, the values of forces, speeds, stresses, and the various external factors affecting technical apparatus are known with very limited accuracy. The measuring devices used in engineering practice have a class of accuracy of the order of 0.2 to 1.0, which corresponds to an error constituting variations of 0.2 to 1% of the full scale of the device.

The results of tests on the ELI-14 apparatus are of interest.

On the basis of test results it was established that the ELI-14(6) vacuum-tube integrator can be used effectively to analyze transient processes in engineering apparatus -- i.e., for the approximate solution of systems of six ordinary linear differential equations with constant coefficients. The equations describing transient processes (attenuating in time) are solved with an error averaging 3-4% of the maximum value of the quantities being measured. In addition, the ELI-14(6) can be used to demonstrate the practical stability of dynamic systems, and to determine the effect of variations in coefficients of equations, and (variations) in initial conditions and right hand members on the course of the transient process (on the solution). In the case of nonstable processes, the electrointegrator can be used to obtain a sufficiently accurate solution for a limited time interval, depending on the character of the equation.

Calculations of Torsion and Bending in Mechanical Constructions

The type EI-12 electrointegrator may be used for torsion calculations on complex shafts and prismatic rods. For these calculations, a section of the shaft or rod is set up on the main panel. A scale is chosen whereby the greatest number of elements will be preserved.

An interesting property of the electric drawing board is that it can be stretched in one direction, compressed in another direction, its form can be changed to represent a circle, an ellipse, or any complex field with a curvilinear outline. These properties are determined by the fact that the electrical coordinates of the model can be represented in any system of curvilinear orthogonal coordinates.

The selection of this or that system of coordinates is determined by the arrangement of the resistances and capacitances in the panel elements. We shall take as an example the solution to the problem of torsion in a propeller consisting of three nonuniform layers.

In graphic representation, the intervals between index points on the x-axis are twice as great as those along the y-axis. Accordingly, the resistances in the direction of x are set up four times less than the resistances of each side of the grid in the y-axis direction. The field modeled by the electric grid is thus "elongated in the direction of the x axis."

The results of the solution are expressed in the form of lines of equal stress values (isolines) at intervals of 20% of the maximum stress value. It is known that the component tangential forces during torsion are proportional to the gradient. To determine rigidity considering torsion, it is necessary to calculate the volume of the figure formed by the stress values obtained.

Problems of bending in plates, beams and other elements can be solved on the EI-12 and on the vacuum-tube integrators. In the study of bending which occurs under loads not changing in time, the EI-12 is used; but it is expedient to use the vacuum-tube models and integrators when studying dynamic processes of bending.

Calculations on parts and units under simultaneous bending and torsion, described by a system of partial differential equations, can be performed on integrators in a fraction of the time taken to perform them with arithmometers.

Calculations in the Field of Regulation

The problems of mechanization and automatization are organically bound up with problems of the regulation of various quantities. As we know, calculations of dynamic processes of regulation are very complex and are often beyond the capacity of engineers. Electrical models, or integrators, can be a great advantage here. With their help it is possible to solve rapidly and with sufficient accuracy the problems encountered in the study of dynamic processes in the field of regulation, and to calculate the parameters of these systems.

The methods for solving such problems on the vacuum-tube-type integrators (ELI-14, ELI-12) is quite simple. The operation reduces to transposing equations, synthesis of the system of regulation, and determination of the parameters of the individual members of the regulator and of the object of regulation. An engineer who has recently finished his formal education can be trained for this operation in a period of several weeks.

After the parameters of the regulating system have been set up, the result of the solution appears on the integrator's oscillograph screen as curves of the transient process for all of the unknown variables of the quantities. It is thus possible to observe directly the processes of interest to engineers during various disturbances and under varying conditions corresponding to emergency or other operating cycles of the system. The determination of the stability of regulation processes according to the criteria of Hurwitz, Routh, or Nayquist is very laborious, but on an electrical model the determination of practical stability is automatic.

In testing the stability of a system, an engineer can select system parameters and contact signs on the basis of design and other considerations so that the system becomes stable.

It should be noted that in engineering practice it is necessary to determine, mainly, the effect of certain quantities on the way a process proceeds, on the stability of a system, etc. Therefore, the possibility of rapid study, on a

model, of the effect of a number of quantities, and the selection of the most suitable operating conditions for a regulating system are of essential value. Electrical integrators are irreplaceable equipment in the hands of engineers for this type of practical analysis.

The fact is that on an electrical model the processes being studied are seen directly on an oscillograph while parameters are being changed by hand. By rotating a commutator knob, any quantity of an element in the system can be varied from -100 to +100% through 1.0% intervals of the given quantity's maximum value. The pictures of the process which appear then are the same as might be expressed by curves in the form of results of the solution of a system of differential equations, which would require several days' work with an arithmometer.

Actually, the labor involved in such investigations has until now often deterred engineers from using methods of scientific analysis, and selection of optimum parameters and operating conditions. The use of models and electro-integrators is playing a great part in the over-all elevation of culture in engineering research and calculations.

The vacuum-tube models permit, among other things, work on testing, adjustment, and refinement of various regulating systems, automatic control devices, and on the study of the dynamics of various automatic machines. For this purpose it is possible to use electrical model-stands as substitutes for the complex objects undergoing regulation and control.

In this case, large machines, motors, and complex mechanical constructions may be replaced by an electrical analogue. The voltages which occur in the model can then play the role of the forces, displacements, and speeds of the mechanical objects. By using follower systems, these voltages can be converted easily into mechanical quantities which will act on the regulators being studied and on other apparatus.

Subsequently, the active parts of the regulators or other apparatus can be attached to responsive elements which convert the mechanical quantities into voltages. The voltages obtained act on the electrical model, thereby creating a closed dynamic system analogous to the real system being studied. However, one of the elements of this closed system -- the regulator or other apparatus -- is real, and all other elements are replaced by the electrical units of the model-stand.

This method for the adjustment and refinement of apparatus for automatic control and regulation is most rational and effective. With the method it is possible to create the most varied operating conditions for the systems without fear of wrecking or damaging machines, motors, and expensive complex mechanical equipment. The conduct of numerous and difficult experiments does not require the consumption of a large quantity of power or fuel.

The electrical modeling method, based on ideas first conceived in the Soviet Union, and developed by Soviet scientists, is bound to play a leading role in engineering practice.

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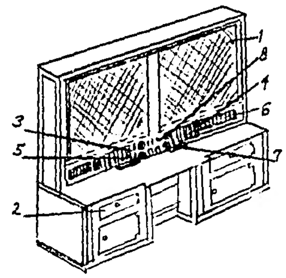

Type EI-12 Electrointegrator

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1. Main panel of resistance boxes

2. Cases with constant condensers

3-6. Devices for setting currents and voltages at all points of the model

7-8. Measuring devices

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